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J.D. Lutz
X. Liu
A.B. Lekov
C. Dunham-Whitehead
J.E. McMahon

Energy Efficiency Standards Group
Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory
Berkeley, California 94720

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A Monte Carlo Approach to the Calculation of Energy Consumption for Residential Gas-Fired Water Heaters

James D. Lutz, P.E.
Associate Member ASHRAE
Alex B. Lekov, Ph.D.
Member ASHRAE
Xiaomin Liu
Camilla Dunham-Whitehead
James E. McMahon, Ph.D.

ABSTRACT

The U.S. government is reexamining energy-efficiency standards for residential water heaters. A key part of this reexamination is to estimate life-cycle cost (LCC) using a Monte Carlo approach to capture the impact of uncertainty and variability in the input variables. This paper discusses the details of this approach for the energy consumption portion of the LCC analysis for several design options for gas-fired water heaters. The results show clear differences in the amount of energy consumption between different design options, even though the ranges of energy consumption for water heaters with any one-design option overlap.

INTRODUCTION

LCC Analysis

The life-cycle cost (LCC) analysis examined the economic impacts on individual consumers from possible revisions to U.S. residential water heater energy-efficiency standards. LCC represents the consumer's cost of purchasing and installing a water heater and operating it for its lifetime. The LCC analysis was done in a spreadsheet that consisted of five modules: hot water use, energy analysis, operating cost, equipment cost, and LCC and payback. In this paper, the energy analysis module is used to demonstrate the use of a Monte Carlo approach, a statistical technique using random sampling to solve problems.

Models Analyzed

Various gas-fired water heater models were analyzed: an "existing baseline" model, which just meets the current efficiency standards; a "2003 baseline" model, which is anticipated to be the standard design in 2003 in the absence of new efficiency standards; and various "design options"—models with improvements to meet possible energy-efficiency standards. Only gas-fired water heaters are discussed in this paper. Designs using HFC-245fa, a current leading candidate to replace HCFC-141b as a blowing agent, are analyzed.

Energy Analysis Module

The energy analysis module calculates how much energy is used in a household by the water heater. Both baseline models and all models with additional design options are considered for each household. This analysis includes use of electricity required by some design options for gas-fired water heaters.

Water heater energy use was estimated using a simplified energy equation, the water heater analysis model (WHAM) (Lutz et al. 1999). WHAM reflects a variety of operating conditions and water heater characteristics. Water heater efficiency characteristics were described using recovery efficiency (RE), standby heat-loss coefficient (UA), and rated input power *(Pon)*. Water heater operating conditions were indicated by average daily hot water draw volume, in let water temperature, thermostat setting, and air temperature around the water heater.

The WHAM equation predicts average daily water heater energy consumption (Q_{in}) and is expressed as follows:

$$Q_{in} = \frac{\mathrm{vol} \cdot \mathrm{den} \cdot \mathrm{Cp} \cdot (T_{tank} - T_{in})}{\mathrm{RE}} \cdot \left(1 - \frac{UA \cdot (T_{tank} - T_{amb})}{\mathrm{Pon}}\right) + 24 \cdot UA \cdot (T_{tank} - T_{amb}) \tag{1a}$$

$$Q_{in} = \frac{\mathrm{vol} \cdot \mathrm{den} \cdot \mathrm{Cp} \cdot (T_{tank} - T_{in})}{\mathrm{RE}} \cdot \left(1 - \frac{\mathrm{UA} \cdot (T_{tank} - T_{amb})}{\mathrm{Pon}}\right) + 86{,}400 \cdot UA \cdot (T_{tank} - T_{amb}) \tag{1b}$$

where:

Q_{in}	=	total water heater energy consumption (Btu/day or J/day)
RE	=	recovery efficiency
Pon	=	rated input power (Btu/hr or W)
UA	=	standby heat-loss coefficient (Btu/hr-°F or W / °C)
T_{tank}	=	thermostat setpoint temperature (°F or °C)
T_{in}	=	inlet water temperature (°F or °C)
T_{amb}	=	temperature of the air surrounding the water heater (°F or °C)
vol	=	volume of hot water drawn in 24 hours (gal/day or m^3/day)
den	=	density of stored water, set constant at 8.29 lb/gal or 993 kg/m^3
Cp	=	specific heat of stored water, set constant at 1.0007 Btu/lb•°F or 4190 J/(kg•K)

ASSESSING IMPACT OF UNCERTAINTY AND VARIABILITY

Two factors can cause variations in a quantitative model—uncertainty and variability. When making observations of past events or speculating about the future, imperfect knowledge is the rule rather than the exception. For example, the energy actually consumed by a particular appliance type (such as the water heater) has been directly recorded in few published studies. Rather, energy consumption is usually estimated based upon available information. Even direct laboratory measurements have some margin of error.

Variability means that different applications or situations produce different numerical values for a quantity. Specifying an exact value for a quantity may be difficult because the value depends on other factors. For example, the amount of hot water used per day by a household depends upon the specific circumstances and behaviors of the occupants (e.g., number of persons, personal habits about hot water use, etc.). Variability within a population makes specifying an appropriate value more difficult. One sample may not be representative of an entire population. On the other hand, variability provides more information about the population under study. Surveys can be helpful here, and analysis of surveys can relate the variable of interest (e.g., gallons of hot water use per day) to other variables that are better known or easier to forecast (e.g., persons per household).

To account for uncertainty and variability, the LCC model was developed in a spreadsheet combined with commercially available add-on software to provide the uncertainty analysis capability. The model used Monte Carlo simulations to perform the uncertainty and variability analysis.

The analysis explicitly specified both the uncertainty and variability in the model's inputs using probability distributions. The Monte Carlo simulation then took thousands of random samples from the probability distribution for each input within the model to calculate the outputs. The distribution of the values calculated for the model's outcome therefore reflect the probability of outcome values that would occur.

In this study, two standard statistical distributions, triangular and normal, were used where a specific form of uncertainty or variability was totally or partially unknown. The triangular distribution is one of the simplest forms of probability distribution. It uses three simple parameters, minimum, most likely, and maximum, to describe the probability distribution for a given set of data. It is commonly used in cases where the knowledge about the factor of interest is limited. Normal distribution, on the other hand, is based on an underlying assumption that the data follow a bell-shaped distribution. This is usually the case in which a variable is influenced by many factors but none of them are dominant. When nothing is known about a random variable except mean and a variance, a normal distribution is used to describe the variable.

Other distributions consider the probabilities within a range of values. For quantities with variability (e.g., electricity prices in different households), surveys can be used to generate a frequency distribution of numerical values (e.g., the number of households with electricity prices at particular levels) to estimate the probability of each value. For quantities with uncertainty, a triangular distribution can be used to provide probabilities (e.g., manufacturing cost to improve energy efficiency to some level may be estimated to be $10 ± $3).

The advantage of this approach is it provides the greatest information about the outcome of the calculations; that is, the probability that the outcome will be in any particular range. The major disadvantage of the approach is that it requires more information—namely, the shape and magnitude of the probability distribution of the values for each quantity.

INPUT VARIABLES

Sample Households

The analysis used as its underlying data source the 1993 *Residential Energy Consumption Survey* (RECS) (DOE 1995). RECS contains a more complete set of data for water heater analysis than other surveys reviewed for this study. RECS data include household characteristics taken from an interview questionnaire and annual fuel consumption and expenditures (excluding transportation fuel) derived from the records of fuel suppliers. Also included are weather data. The RECS survey consists of a total of 7,111 sample households from the contiguous U.S.

Most, but not all, RECS household records were used in the analysis. Households that did not have the following three defining features were excluded:

1. Running hot water
2. An individual water heater
3. A water heater that uses electricity, oil, gas, or LPG

Weightings were provided for each RECS household. These values indicate how commonly each household configuration occurs in the general population. The assumption was made that the households used in the analysis, with their weighted averages, were representative of housing nationwide.

RECS data sometimes report ranges rather than precise numbers for variables and lacks some crucial information needed for our analysis. To correct for these missing or insufficient data, two methods were applied: (1) when ranges were given, best-point estimates within the range were made; and 2) when RECS data did not provide particular information of interest, other studies were used to develop the necessary information.

RECS also provides data on the number, age, and employment status of household occupants, the presence of a clothes washer or dishwasher, and the form of payment to fuel utilities.

Operating Conditions

Average Daily Hot Water Use. Hot water use varies widely among households because it depends on household and water heater characteristics, including the number and age of the people who live in a home and the way they consume hot water, the presence of hot water-using appliances, the water heater size and thermostat set point, and the climate in which the home is situated. By accounting for these five types of characteristics, the hot water module estimated average daily volume of hot water used by households (Lutz et al. 1996).

There was a degree of uncertainty in this estimation of hot water use because of variability in demographic and climatic inputs and the uncertainty of the estimated coefficients in the equation. The uncertainties in the coefficients were defined using normal distributions with the parameters provided in a regression analysis described in the original study (Ladd and Harrison 1985).

Figure 1 shows a histogram of estimated daily hot water use for households with gas-fired water heaters. For these households, the average daily use was 48.6 gallons of hot water.

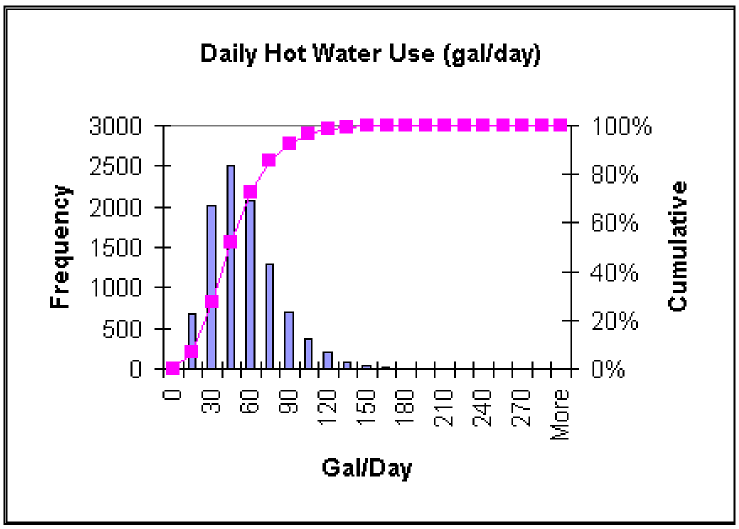

Figure 1. Daily Hot Water Use

Temperatures. The temperature of the inlet water, water heater thermostat setpoint, and temperature of the air surrounding the water heater determine the water heater operating conditions. These data, however, are not listed in the RECS public data. Since the analytical approach was based on individual RECS households, it was necessary to develop a methodology to determine these values.

RECS does provide data on heating and cooling degree-days. The degree-day data were used to identify the climate for each household in the sample. The weather for each RECS household was determined by matching RECS heating and cooling degree-day data to weather data for 42 U.S. cities (NOAA 1998).

Once each RECS household was associated with a climatic zone (see Figure 2), inlet water temperatures were assigned based on 30-year average annual outside air temperatures. The inlet water temperature was assumed to be the same as groundwater temperature, which varies according to geographic region. Groundwater temperatures were assumed to be slightly warmer than air temperatures. Two degrees were added to the average annual outside air temperature data to calculate the inlet water temperature (Labs 1979). The estimates were compared with published annual average groundwater temperatures for various regions in the country (Abrams and Shedd 1992). The comparison showed that, in the majority of cases, the difference between the two values was less than 2°F (1°C).

Figure 2. Climate Zones for Analysis

Water heater thermostat settings were assigned to RECS households based on their inlet water temperature and an equation derived from a study of California houses (CEC 1990). The graph of the data displayed in Figure 3 shows the correlation between thermostat setpoint and inlet water temperature. The data indicated that people with colder inlet water tend to set their water heaters to higher setpoint temperatures. Either hotter water or more hot water must be mixed with the colder water to have enough warm water for household use. The derived equation is shown below. The equation indicates that, if the inlet water temperature for the household was 58°F (14.4°C), then the water heater's setpoint temperature was 134.1°F (56.7°C). For every degree Fahrenheit drop in inlet water temperature, the setpoint temperature increases slightly more than one-half of a degree Fahrenheit.

$$T_{tank} = 134.1 + 0.55 * (58 - T_{in}) \quad (2a)$$

$$T_{tank} = 56.7 + 0.34 * (14.4 - T_{in}) \quad (2b)$$

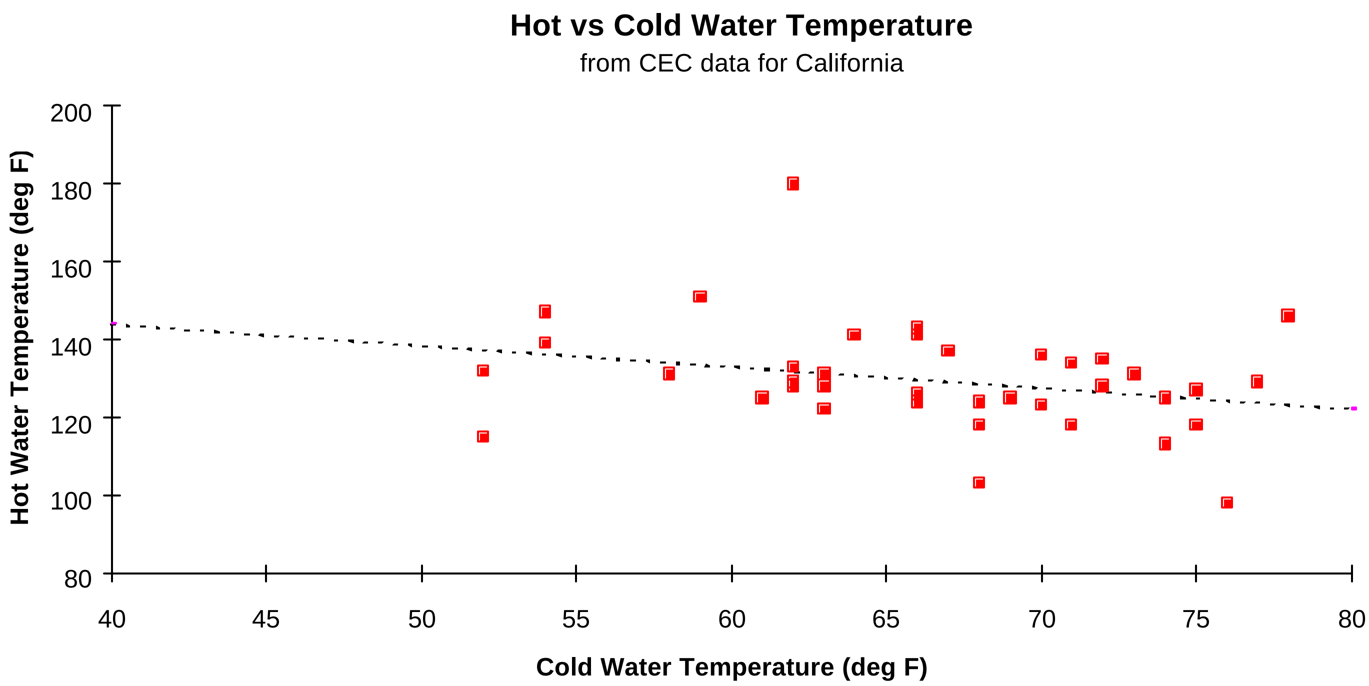

Figure 3. Comparison of Setpoint and InletWater Temperatures

Because individual households maintain a wide range of thermostat settings, a random error with a mean of 0 and a standard deviation of 13°F (7.2°C) was added to the water heater setpoint temperature to account for this variability.

A set of assumptions was developed to determine air temperature around water heaters based on calls to 50 water heater installers from around the country regarding typical locations for water heater installation. The air temperature around the water heater was determined based on the following assumptions:

1. RECS reports the presence or absence of basements in houses and, if there is a basement, whether or not some portion of it is heated. If a house had a basement, the water heater was assumed to be located in the basement. For unheated basements, a temperature was assigned that is the average between the annual outside air temperature for that climatic zone and an assumed house air temperature of 72°F (22.2°C).

2. If RECS reports the basement as a heated space, then the temperature of the air around the water heater was assumed to be the temperature of the house, 72°F (22.2°C).

3. If the house had no basement but did have a garage (either attached to the house or not), the water heater was assumed to be in the garage. A temperature of 5°F (2.8°C) higher than the average annual outside air temperature for that house was assigned to the air surrounding the water heater.

4. In the absence of a basement or garage, it was assumed that the water heater was in the house (in the kitchen or a utility closet), and a temperature of 72°F (22.2°C) was assigned to the surrounding air.

Table 1 shows the percentages of assigned water heater locations for each household listed in RECS.

Table 1. Water Heater Location in House

Water Heater Location	Percent (%)
Unheated Basement	20.9
Heated Basement	26.0
Garage	24.7
Inside House	28.3

Water Heater Characteristics

RECS only reports three ranges of water heater tank size: small, medium, and large. Those three ranges were matched with standard sizes listed in Table 2 and assigned as an exact water heater size to each RECS house. The standard sizes corresponded to the most common models listed in a water heating equipment directory (GAMA 1999). By using standard sizes in the analysis the broad range of water heater sizes can be accurately reflected.

Table 2. Water Heater Sizes

RECS	**Standard Sizes** *gallons (liters)*
Small	30 (110)
Medium	40(150)
Large	50(190)
	75(280)

Design Options. Six design options were examined in the energy analysis. They are all currently, or have recently been, applied to commercial or residential water heaters. In the engineering analysis phase, certain design options (listed in Table 3) were combined in order of simple payback estimate. The entire analysis was not completed for other design option combinations that provide similar efficiency levels.

Heat Traps. Heat traps are anti-convection devices that reduce standby losses that occur through the plumbing connections when no hot water is being drawn.

Increased Jacket Insulation. Increasing the thickness of insulation on water heaters will reduce heat losses through the jacket. Three different thickness levels were analyzed.

Improved Flue Baffle. The standard flue baffle is a twisted strip of metal in the flue that increases the turbulence of flue gases and improves heat transfer. Changing the geometry of the flue baffle can modify its effectiveness.

Side Arm Heater. The side arm heater design heats water in a small separate heat exchanger. This reduces flue losses significantly.

Electronic Ignition. Electronic ignition uses a spark or hot surface (instead of a standing pilot) to ignite the burner. These devices operate only when the burner is being ignited.

Plastic Tank. The lower conductivity of plastic compared to metal reduces the heat lost through the tank wall.

Table 3. Combinations of Design Options

00	Existing Baseline	Baseline (141b)
0	2003 Baseline	2003 Baseline
1	Heat Traps	2003 Baseline + Heat Traps
2	78% RE	2003 Baseline + Heat Traps + 78% RE
3	78% RE, 2" Insulation	2003 Baseline + Heat Traps + 78% + 2" Insulation
4	78% RE, 2.5" Insulation	2003 Baseline + Heat Traps + 78% RE + 2.5" Insulation
5	80% RE, 2" Insulation	2003 Baseline + Heat Traps + 80% RE + 2" Insulation
6	80 RE, 2.5" Insulation	2003 Baseline + Heat Traps + 80% RE + 2.5" Insulation
7	80% RE, 3" Insulation	2003 Baseline + Heat Traps + 80% RE + 3" Insulation
8	Side Arm	2003 Baseline + Heat Traps + 80% RE + 3" Insulation + Side Arm + Electronic Ignition + Plastic Tank

Determining Efficiency Characteristics

The energy analysis uses the WHAM equation to calculate energy consumption for all design options as a function of RE, UA, and *Pon*. To account for uncertainty and variability, the uncertainty ranges for those three energy parameters.

The analysis uses RE and UA results from computer simulations under test procedure conditions (CFR 1998a). Detailed computer simulations were performed for each design option and all combinations of design options on all of the standard-size models were estimated as part of the engineering analysis (Paul et al. 1993).

The primary data source for *Pon* was water heater manufacturers' product literature (DOE 1999). Typical values were assigned for all standard water heater sizes analyzed. Table 4 is a summary of the values for UA, RE, and *Pon* for all standard water heater sizes studied in this analysis.

The program reports the results according to the standard water heater test procedure (CFR 1998b). The outputs include RE and UA, as well as EF

Table 4. Water Heater Efficiency Characteristics

Rated Volume		UA			Pon	
gallon	liter	Btu/hr °F	W/K	RE	Btu/hr	W
30	110	11.56	6.098	0.758	30,000	8,800
40	150	13.86	7.312	0.756	40,000	11,700
50	190	16.14	8.514	0.723	50,000	14.700
75	280	21.80	11.50	0.672	75,000	22,000

Efficiency Parameters Distributions

Estimated uncertainty ranges for EF for different design options were provided for 40-gallon (150-liter) gas-fired water heaters (Minniear 1997). The ratio of maximum and minimum EF for each design option compared to the EF of the baseline for the typical tank size was assumed to be applicable to that design option on other standard size water heaters. Since each design option could be a combination of several single designs, the range of EF of a design option combination was assigned the largest ratio among the single design options included in the combination. This ensured that the estimated uncertainty ranges include the effect of uncertainty from every single design.

The resulting uncertainty for EF was characterized as a simple triangular probability distribution. In gas-fired water heaters, the largest range of EF was within 5% of the value from the computer simulation study.

The uncertainties for RE and UA were developed from the uncertainty for EF. Variations in RE and UA were calculated that would independently cause the desired variation of EF and then the range of the RE and UA terms were reduced by $1/\sqrt{2}$. This adjustment assumed the RE and UA distributions have approximately equal impacts on ER

The equations to solve RE for a given EF are as follows:

$$RE_{max} = RE_{likely} \times \left(1 - \frac{1}{\sqrt{2}}\right) + \frac{\mathrm{EF}_{max} \times 41{,}094 \times (UA \times 67.5 - \mathrm{Pon})}{\mathrm{Pon} \times (1{,}620 \times \mathrm{EF}_{max} \times UA - 41{,}094) \times \sqrt{2}} \tag{3a}$$

$$\mathrm{RE}_{min} = \mathrm{RE}_{likely} \times \left(1 - \frac{1}{\sqrt{2}}\right) + \frac{\mathrm{EF}_{min} \times 41{,}094 \times (UA \times 67.5 - \mathrm{Pon})}{\mathrm{Pon} \times (1{,}620 \times \mathrm{EF}_{min} \times UA - 41{,}094) \times \sqrt{2}} \tag{3b}$$

Similarly, the uncertainty for UA can be determined by the following set of equations:

$$UA_{max} = UA_{likely} \times \left(1 - \frac{1}{\sqrt{2}}\right) + \frac{Pon \times \left(\frac{RE}{EF_{min}} - 1\right)}{67.5 \times \left(RE \times Pon \times \frac{24}{41{,}094} - 1\right) \times \sqrt{2}} \tag{4a}$$

$$UA_{min} = UA_{likely} \times \left(1 - \frac{1}{\sqrt{2}}\right) + \frac{Pon \times \left(\frac{RE}{EF_{max}} - 1\right)}{67.5 \times \left(RE \times Pon \times \frac{24}{41{,}094} - 1\right) \times \sqrt{2}} \tag{4b}$$

Pon has far less effect on EF than the other two parameters. Therefore, the range of uncertainty for *Pon* was taken directly from the data for water heaters listed in the standard industry directory.

The variations in RE, UA, and *Pon* for a range of EF are shown in Table 5.

ENERGY CONSUMPTION AND SAVINGS

Table 6 lists the average annual energy use for gas-fired water heaters.and the average daily energy savings for each design option compared to the 2003 baseline water heater with HFC-245fa insulation.

The full distributions of energy consumption for each design option are shown in Figure 4.

IMPORTANCE ANALYSIS

Figure 5 shows the results of the importance analysis for energy consumption for 78% RE and 2" insulation on gas-fired water heaters using R-245fa as a blowing agent. The variables are listed by rank order correlation with maximum values for energy consumption, positive or negative, on top and minimum on the bottom. It is apparent that hot water use has the most significant impact on energy consumption, followed by standby heat loss coefficient rated input power and inlet and setpoint temperatures. Rated input power is as significant as the standby heat loss coefficient.

Table 5. Water Heater Energy Characteristics

Design Options		EF	RE	UA		Pon	
				Btu/ hr-°F	W/K	Btu/hr	W
	maximum	0.5485	0.7648	13.464	7.103	60000	17,600
Existing Baseline	most-likely	0.5431	0.7571	13.993	7.382	40000	11,700
(HCFC-141b)	minimum	0.5377	0.7495	14.347	7.568	28000	8,200
	maximum	0.5483	0.7649	13.670	7.211	60000	17,600
2003 Baseline	most-likely	0.5429	0.7572	14.017	7.394	40000	11,700
(HFC-245fa)	minimum	0.5377	0.7496	14.371	7.581	28000	8,200
	maximum	0.5588	0.7655	12.730	6.715	60000	17,600
Heat Traps	most-likely	0.5519	0.7561	13.155	6.940	40000	11,700
	minimum	0.5450	0.7468	13.591	7.170	28000	8,200
	maximum	0.5756	0.7871	12.128	6.398	60000	17,600
78% RE	most-likely	0.5643	0.7717	12.788	6.746	40000	11,700
	minimum	0.5530	0.7566	13.475	7.108	28000	8,200
	maximum	0.6100	0.8023	9.974	5.261	60000	17,600
78% RE, 2" Insulation	most-likely	0.5922	0.7799	10.907	5.754	40000	11,700
	minimum	0.5744	0.7579	11.898	6.277	28000	8,200
	maximum	0.6192	0.8078	9.461	4.991	60000	17,600
78% RE, 2.5" Insulaton	most-likely	0.5982	0.7818	10.534	5.557	40000	11,700
	minimum	0.5773	0.7564	11.685	6.164	28000	8,200
	maximum	0.6292	0.8271	9.536	5.030	60000	17,600
80% RE, 2" Insulation	most-likely	0.6080	0.8002	10.590	5.587	40000	11,700
	minimum	0.5867	0.7740	11.721	6.183	28000	8,200
	maximum	0.6375	0.8308	9.090	4.795	60000	17,600
80% RE, 2.5" Insulation	most-likely	0.6145	0.8022	10.205	5.383	40000	11,700
	minimum	0.5914	0.7743	11.406	6.017	28000	8,200
	maximum	0.6448	0.8350	8.691	4.585	60000	17,600
80% RE, 3" Insulation	most-likely	0.6185	0.8027	9.940	5.244	40000	11,700
	minimum	0.5922	0.7713	11.300	5.961	28000	8,200
	maximum	0.7488	0.8305	2.787	1.470	60000	17,600
Side Arm	most-likely	0.7149	0.8000	3.989	2.105	4000	11,700
	minimum	0.6809	0.7699	5.311	2.802	28000	8,200

Table 6. Average Energy Consumption and Savings for Water Heaters

	Design Option	Average Daily Use			Average Savings	
		MMBtu/yr	(GJ/yr)	kWh/yr	Btu/day	(kJ/day)
0	2003 Baseline	22.6	(23.8)	0.0	–	–
1	Heat Traps	22.1	(23.3)	0.0	1304	(1376)
2	78% RE	21.7	(22.9)	0.0	2431	(2546)
3	78% RE, 2" Insulation	20.5	(21.6)	0.0	5868	(6191)
4	78% RE, 2.5" Insulation	20.2	(21.3)	0.0	6552	(6913)
5	80% RE, 2" Insulation	20.0	(21.1)	0.0	7247	(7646)
6	80 RE, 2.5" Insulation	19.7	(20.8)	0.0	7941	(8378)
7	80% RE, 3" Insulation	19.5	(20.6)	0.0	8381	(8843)
8	Side Arm	16.1	(17.0)	21.0	17485	(18,448)

Statistical Analysis

A statistical analysis of the results for gas-fired water heaters was conducted to verify that the differences between design options were true differences and not the result of sampling variation. Results for 10,000 simulations of energy consumption under eight different gas-fired water heater design options were examined to determine which design option generated lower energy consumption.

Since each simulation consists of the same input variables (representing one household) measured at both a baseline and at eight different design options, the variables used in the analysis were calculated by subtracting the appropriate baseline value from the value obtained under one of the proposed design options. This achieves two very important goals. First, since each household serves as its own control, the precision of statistical tests was dramatically increased, allowing techniques such as t-tests and analysis of variance (ANOVA) to effectively detect differences undetected from samples not having built-in controls. Second, using differences instead of the original values eliminates possible problems due to correlation among the simulations. Delta Q was examined, representing the difference in energy consumption between a design option and its baseline value.

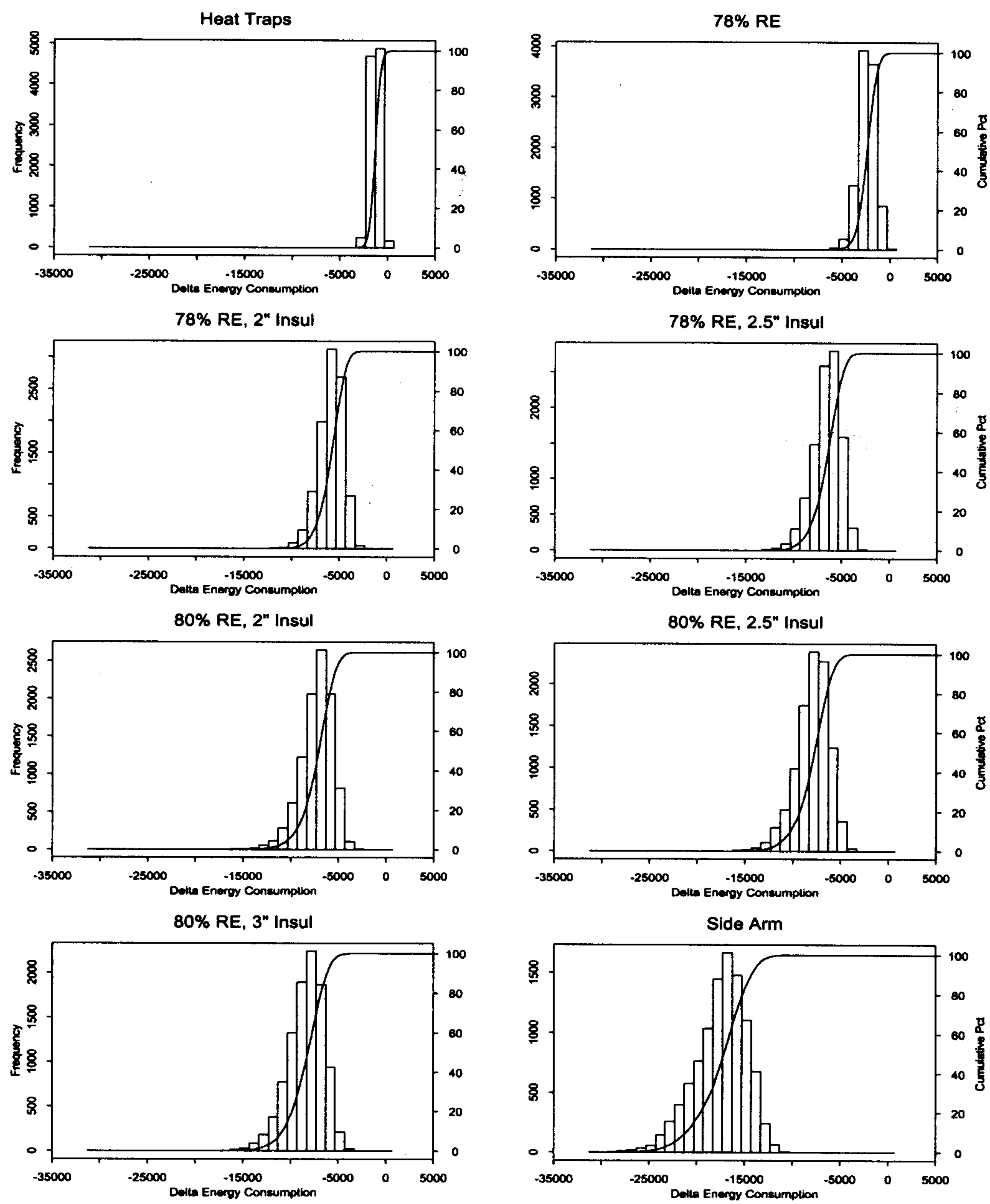

Figure 4. Full distribution of energy consumption for each design option.

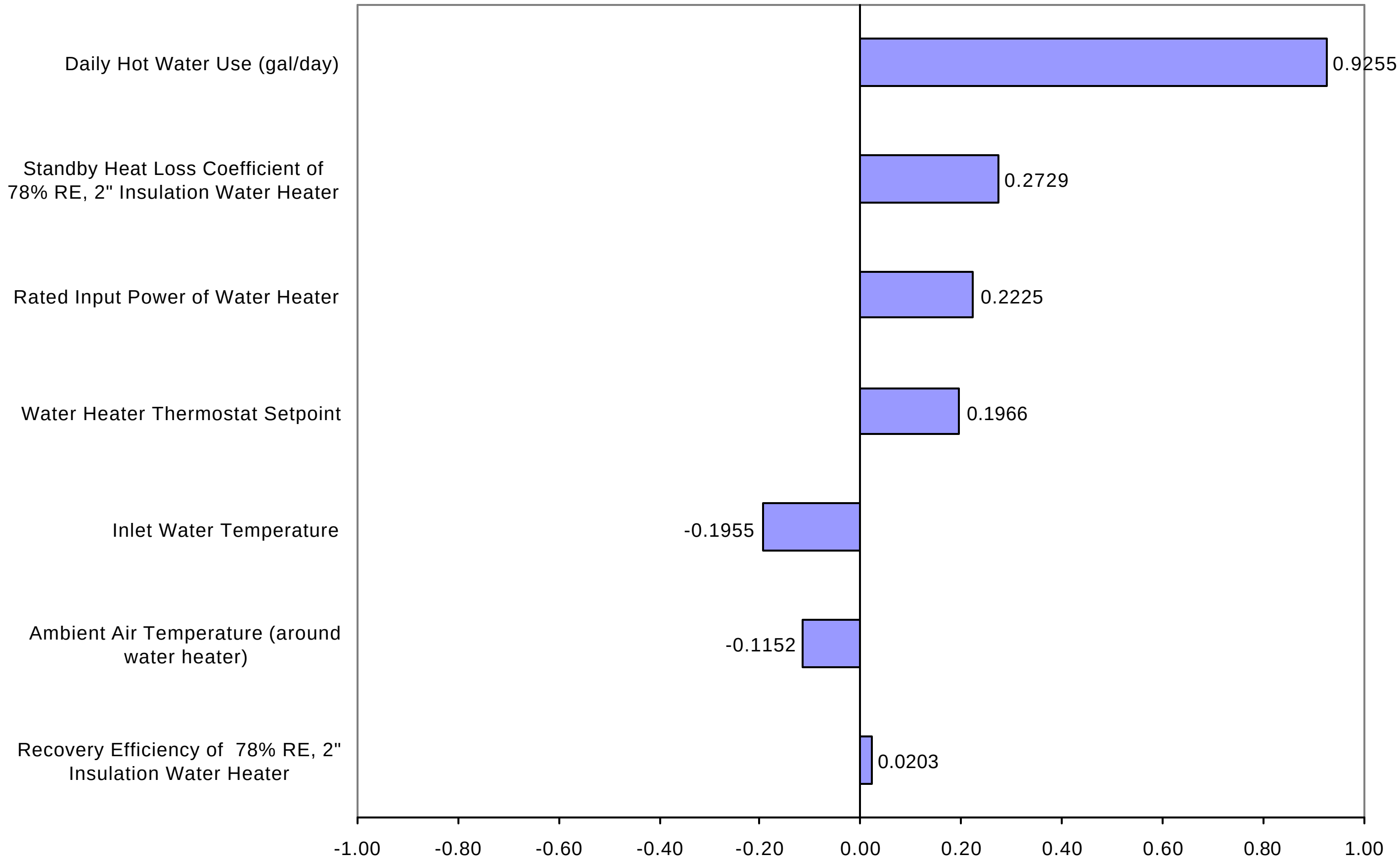

Figure 5 **Importance of Input Parameters to Annual Energy Consumption**

DISCUSSION

With data representing differences from a baseline value, there were usually two main questions of interest. First, since a difference of zero represents no change, it was of interest to determine if the mean difference observed under a particular design option was different from zero. The appropriate statistical test for this purpose was a one-sample t-test. The results of one-sample t-tests for the Delta Q values are summarized in Table 7.

The extremely low probability levels (Pr (mean = 0)) seen in the tables are an indication that the means were significantly different from zero. Thus, for each of the design options, the mean value reported can be considered to be different from zero. For the energy consumption variables, it was clear that each of the design options shows lower energy consumption, and, proceeding through the design options going from 1 to 8, the reduction in consumption increases, with design option 8 showing the largest reduction.

Table 7. Sample t-test Results for Delta Q

Delta Q					
Design Option	**Upper 95% Confidence Interval (Btu/day)**	**Lower 95% Confidence Interval (Btu/day)**	**Average (Btu/day)**	**t-value**	**PR (average = 0)**
1	1294.61	1313.76	1304.19	267.01	<.0001
2	2413.42	2447.84	2430.63	276.85	<.0001
3	5842.90	5892.69	5867.80	462.00	<.0001
4	6523.70	6580.27	6551.99	454.04	<.0001
5	7214.91	7278.82	7246.86	444.50	<.0001
6	7906.96	7975.52	7941.24	454.05	<.0001
7	8344.26	8417.96	8381.11	445.79	<.0001
8	17,432.25	17,537.59	17,484.92	650.70	<.0001

Having established that the changes in energy consumption values were actually different from zero, the other statistical question of interest has to do with comparisons among the different design options. Having established that both of these values were significantly different from zero, it was of interest to test to see if these two mean values differ from each other. The appropriate statistical technique to test questions of this type was ANOVA, followed by a suitable multiple comparison procedure. Table 8 presents the results of this analysis.

The very low probability values (Pr > F) in Table 8 indicates that there were significant differences among the means of energy consumption under the eight design options. In addition, the tests detect no overlap among the means for the variable studied. Thus, differences between the various design options can be treated as true differences and not the result of sampling variation.

Table 8. ANOVA for Delta Q

Source	df	Sum of Squares	Mean Squares	F-value	Pr > F
Design Option	7	1.674093E+12	2.391561E+11	90,346.10	0.0001
Residuals	79,992	2.117477E+11	2.647111E+06		
Total	79,999	1.885841E+12			

CONCLUSION

When the simulation results were viewed as paired observations between a baseline and a proposed design option (representing different design options), each of the design options produces changes in energy consumption values that were significantly different from zero. Energy consumption values decreased for all design options.

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